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The Lightweight Design of a Dump Truck Frame based on Dynamic Responses

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Abstract—**This paper develops a new scheme for the lightweight design of heavy dump truck frames based on the characteristics of dynamic responses. The dynamic response is predicted using a finite element (FE) model which is verified by an experimental mode analysis. The FE model is then used to investigate the characteristics of dynamic responses and frame weight changes with respect to the mass changes of each frame component for selecting significant components. An optimization is finally developed for the lightweight design under constrains that maintain required dynamic responses and static strength. The optimization results show that the weight of frame can be reduced by 8%, showing that the scheme is an effective way to achieve automotive lightweight design.**

Keywords-Lightweight; Truck frame; FE Optimization

I. INTRODUCTION

With continuously rising fuel prices and demanding greenhouse gas emissions reduction, a great deal researches have been conducted to develop more economical automobiles. Obviously, the weight reduction of automotive body structures is an effective way to improve fuel efficiency and emission pollutions. In particular, the lightweight design in automobile development plays an important role in decreasing the weight of a full vehicle [1]. It is reported that fuel consumption may decrease by 6–8% once the lightweight effects of full vehicle can reach about 10% weight reduction [2]. Various lightweight automotive bodies have been developed using high strength steels [3, 4], lightweight aluminum alloys [5, 6] and composite materials [7]. These special materials can provide lighter weight car bodies. However, the cost of these special materials is one of the main barriers to replace common steels using these materials [8, 9].

The frame of automobiles supports all of assemblies and undertakes the flexural and torque moments due to power transmission components. Moreover, it undertakes the random dynamic incentives caused by complicated road conditions [10]. So the frame structure has a critical impact on the performance of a whole vehicle. Its strength performance determines the strength and anti-fatigue performance of the whole vehicle. Meanwhile, as the frame is one of the largest assemblies and its weight is the main portion of the whole vehicle, the lightweight design and optimization of frame structures are significantly promising in reducing overall weight of a vehicle [11].

Obviously, any modifications to a structure by means of lightweight design must be under constrains that maintain the frame strength and dynamic characteristics. Sensitivity analysis is a useful way for the structure modification and design optimization. It can help to improve the optimization efficiency significantly. This paper presents a new approach to the lightweight design of heavy dump truck frames based on the study of dynamics responses. It predicts dynamic responses using a finite element (FE) model which is verified subsequently by an experimental mode analysis. The validated FE model is then used to investigate the characteristics of dynamic response with respect to the mass change of each component by means of a sensitivity analysis. An optimization scheme is then developed to modify the sensitive components of the frame for the lightweight design under constrains. The result shows that the weight of the frame can be reduced significantly through the optimization.

II. THE MODAL ANALYSIS OF DUMP TRUCK FRAME

A. The Modal Analysis

Vibration modals are the inherent characteristics of elastic structures. Modal analysis is an important practice that allows the main characteristics of structures in a vulnerable frequency range to be identified, and it can also predict the actual vibration responses in a frequency band when the structure is applied by external or internal various vibration exciting sources. In theory, modal analysis is conducted through a coordinate transformation to convert corresponding vector described in the original physical coordinate system into the modal coordinate system for calculating the values of the structure vibration models. Without considering the effects of damping, a typical equation governing vibration responses can be expressed as:

$$[M]\{\ddot{X}\}+[K]\{X\}=\{0\} \tag{1}$$

In (1) M, K, $\ddot{X}$ and X denote mass matrix, stiffness matrix, acceleration vector and displacement respectively. When the structure vibrating on the fixed frequency that means:

$$\{X\}=\{\varphi\}\sin\left(\omega t+\phi\right) \tag{2}$$

So that $\ddot{X}$ can be expressed:

$$\{\ddot{X}\}=-\omega^2\{\varphi\}\sin(\omega t+\phi) \tag{3}$$

From (1), (2) and (3) the free vibration characteristic equation can be obtained:

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$$\left([\mathrm{K}] - \omega^2 [\mathrm{M}]\right)\{\varphi\} = \{0\} \tag{4}$$

The solution of (4) can be obtained by setting the determinant matrix of (4) to be zero:

$$\det\left([\mathrm{K}] - \omega^2 [\mathrm{M}]\right) = 0 \tag{5}$$

(5) is the structural vibration characteristic equation and the characteristic value of ω_i^2 meet the following:

$$[\mathrm{K}]^{-1}[\mathrm{M}]\{\varphi_i\} = (1/\omega_i^{\ 2})\{\varphi_i\} \ \ldots\ldots\ldots\ldots(6)$$

where the feature vector or mode shape $\{\varphi_i\}$ is the vibration mode vector corresponding to the structural circular frequency ω_i of the vibration structure. This shows that once the modal parameters of $\{\varphi_i\}$ and ω_i is known the dynamic responses of a structure can be predicted under differ excitations.

B. FE Analysis

As indicated in Fig. 1, the dump truck frame concerned is a side beam. It has two main longitudinal beams, two root lining beams, 6 horizontal beams and related links board that joint together by rivets. The height of longitudinal beam is 300 mm. The width of wing is 80 mm with lining construction. And the material for all components is 16Mn. The whole frame structure has a construction with wider front and narrower back-end. The width at the front is 1000mm while 850mm at the back-end with a wheelbase distance is 3800 + 1350 mm.

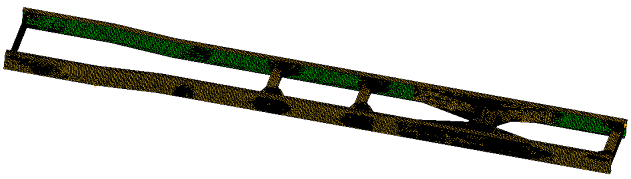


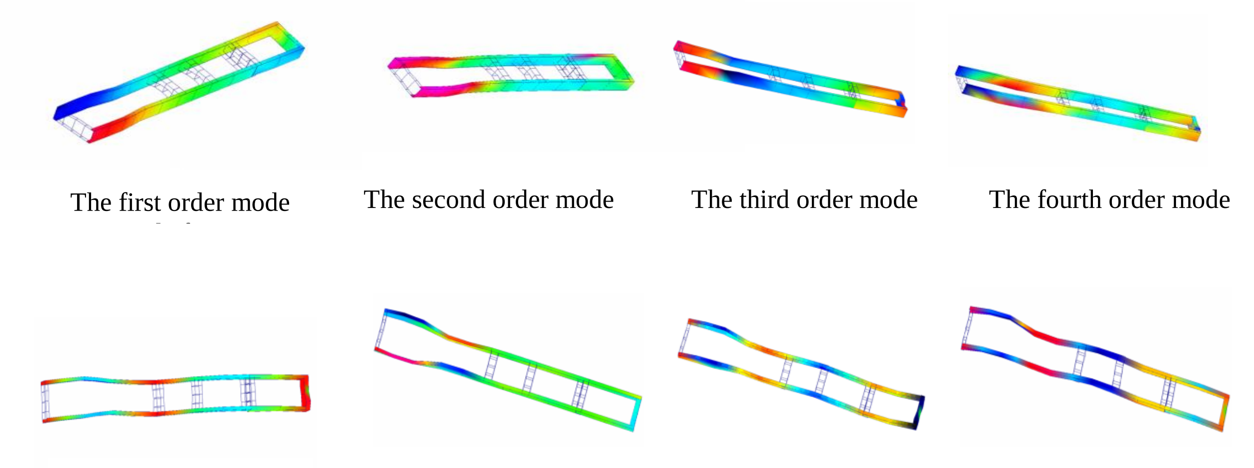
Figure 1. FE model of frame from HyperWork software package

Fig.1 shows the grid arrangement of the FE model. Using the grid arrangement and necessary calculation parameters, the first ten vibration modes in the low frequency range below 100Hz can be obtained by HyperWork software. Fig. 2 shows the detailed features of each mode which is also explained further in Table 1. These low frequency inherent modes are interested because their frequency values are close to potential exciting sources such as the oscillations of different road conditions and vibrations from engine and power transmission. In addition, it can be seen that the mode shapes are close to its real application and indicated the model and calculation process are acceptable.

C. Test Modal Analysis

To verify the FE model for lightweight design, a test modal analysis was also applied to the frame. The test system consists of three main parts: vibration excitation, vibration measurement and model analysis system. An impact hammer was used to produce excitation and a DASP system was used to record data and setup the model parameter.

In order to obtain all the modal parameters, a sufficient number of transfer functions have to be obtained in various measurement points throughout the frame. Refereeing the structure feature and FE model, the model test selected 92 measuring points and obtained 276 transfer functions. Based on these transfer functions the impulse response functions are calculated and then modals are obtained by a frequency domain modal fitting methods based on an eigensystem realization algorithm (ERA). It results in 8 modes in the low frequency range as shown in Fig. 2. Comparing with the calculated results from FE model, it shows that the frequency values are very close to each other which confirmed that the FE model is sufficiently accurate to be referred for the frame optimization to minimise the overall weight.



The first order mode | The second order mode | The third order mode | The fourth order mode

The fifth order mode | The sixth order mode | The seventh order mode | The eighth order mode

Figure 2. Vibration modes of dump truck frame

TABLE I. THE CALCULATION RESULTS AND THE TEST MODAL RESULTS

Order	**FE ω_r(Hz)**	**Test ω_a(Hz)**	**Difference(%)**	**Vibration model description**
1	8.20	9.33	12.11	The first order twist
2	10.73	11.88	9.68	The first order lateral bending
3	26.90	——	——	The first order vertical bending with local twist
4	31.03	——	——	The second order lateral bending with local bending
5	37.47	38.46	2.57	The second order lateral bending with local bending
6	43.30	44.53	2.76	The second order twist
7	47.94	52.71	9.04	The second order lateral bending
8	67.93	70.12	3.12	The second order vertical bending with local twist
9	72.79	75.44	3.51	The third order lateral bending
10	87.22	89.08	2.08	The four order lateral bending

III. LIGHTWEIGHT DESIGN OF DUMP TRUCK FRAME

A. Sensitivity Analysis

The objective of lightweight design is to reduce the mass of the frame as much as possible under the constrain condition that maintains the structure performance as high as possible. By comparing the influences of each component on the frame, it is possible to find out the components which can be redesigned optimally with minimal weight. It means that the reduction of the identified components in height, thickness and length can achieve the mass reduction with minimal influence on the stiffness strength requirement. Theoretically, many possible components can be adjusted during optimization. However, because the complexity of the frame in mass distribution and shape diversities, it is difficult to determine the influences of their changes on frame stiffness and inherent frequency. Therefore, it is necessary to determine the sensitivity of each component in influencing the structure performance and hence to identify the components which can have the most significant influences on the mass of frame in the low orders of inherent frequencies [12].

The sensitivity analysis is to examine the gradient of concerning responses with respective to structural characteristic parameters such as x_j. In particular, it is the partial derivative values of a component mass or the frequency value of the first order model to the change in component variation thickness. If a frame structure performance parameter denoted by u_i, the gradient to a structural parameters x_j can be expressed as:

$$\mathrm{Sen}(u_i / x_j) = \frac{\partial u_i}{\partial x_j} \tag{7}$$

The implementation of sensitivity analysis for frame structure is based on the tool of gradient evaluation provided by the optimization module of the design in OptiStruct software. Using FE model, it calculates the gradient of target function respective to state variables at a structure reference point that is denoted by X, thus sensitivity can be calculated by:

$$\mathrm{Sen}(u_i / x_j) = \frac{\partial u_i}{\partial x_j} = \frac{u_i(X + \Delta x_j \bullet e) - u_i(x)}{\Delta x_j} \tag{8}$$

where X is a vector representing all the design parameters such as x_j of the frame structure; Δx_j is the variation of structural design parameters with a default value of 1% to the difference of x_j between ceiling and floor limit; and e is a unity vector of the same dimension as X. Using (8) sensitivity computation can be performed by changing design variables by 1% in turn to obtain sensitive values respectively.

TABLE II. THE RESULTS OF SENSITIVITY ANALYSIS

No.(x_j)	**Sen(kg/mm)**	**$\mathbf{Sen_1}$(Hz/m)**	**$\mathbf{Sen_2}$(Hz/m)**
1	52.30	50.90	67.90
2	47.90	21.40	-0.82
3	1.51	-2.55	84.40
4	1.32	11.60	0.36
5	1.32	28.10	-6.90
6	2.66	27.60	0.80
7	2.66	25.00	0.57
8	2.53	6.90	-17.10
9	15.50	85.20	-4.62
10	0.35	-4.47	22.50
11	1.13	7.77	25.10
12	0.96	7.23	9.74
13	1.13	3.33	-3.78
14	0.96	14.20	-2.76
15	0.88	3.92	-5.24

During the sensitivity calculation for the frame structure, the thickness of each component of frame is set as the design variables whereas the target function including three parameters: the mass of frame, the frequency value at first order twist modal and the frequency at the first bending modal. These parameters allow maintaining the dynamics responses and the strength performance.

The sensitivity analysis respective to each component are presented in Fig. 3 and detailed in Table Ⅱ. It can be seen from these results that the sensitivity amplitudes for the three target responses of interesting vary with components number significantly and change greatly with respect to the response. As shown in (8), these amplitudes are resulted from small changes in designing components and hence indicate that different designing components have different degrees of responses.

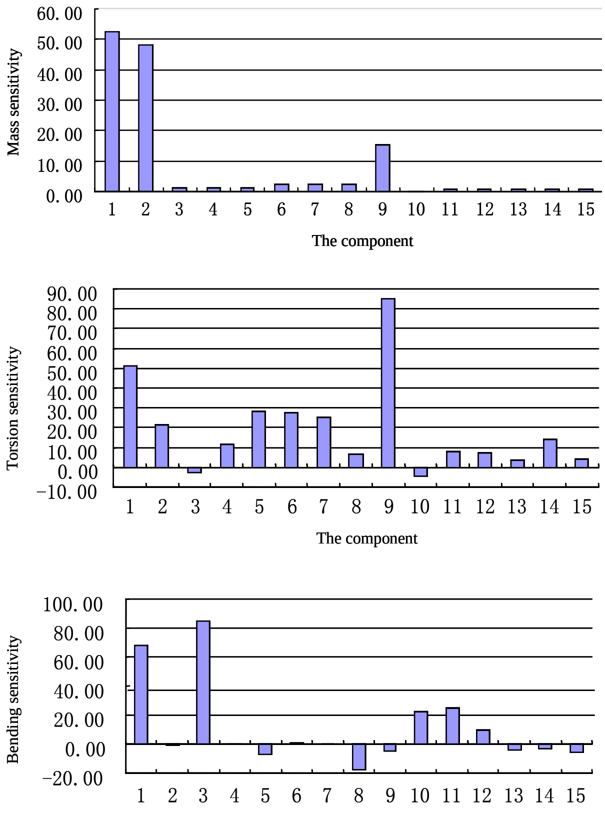


Figure 3. The sensitivity analysis results for each component

On the other hand, several components have very low amplitudes for all of the three responses. It means that they have little influences and can be excluded in the optimization process. Therefore, the design components for lightweight optimization are identified as these with high sensitivity values. They include the longitudinal beam labeled as No.1 in Table II, the root lining beam labeled as No.2, the first horizontal beam labeled as No.3, the third horizontal beam as No.5, the fourth horizontal beam as No.6, the fifth horizontal beam as No. 7, the links board as No. 9, the first beam link board as No. 10, the top links board of the second beam as No. 11 and the top link board of the third horizontal beam as No. 12.

B. *Lightweight Design*

1) *Optimization Model*

To minimise the weight of frame, an optimization model is implemented with following parameters:

- The objective function is to reduce the frame mass;
- The optimization constraint conditions are the first order torsion and the first order bending strength, the lower frequency of first twist mode is 8.20 Hz, the lower frequency of first bending is 10.73 Hz;
- The component thickness as the design variable.

The optimization algorithm is based on the OptiStruck module in HyperWork software.

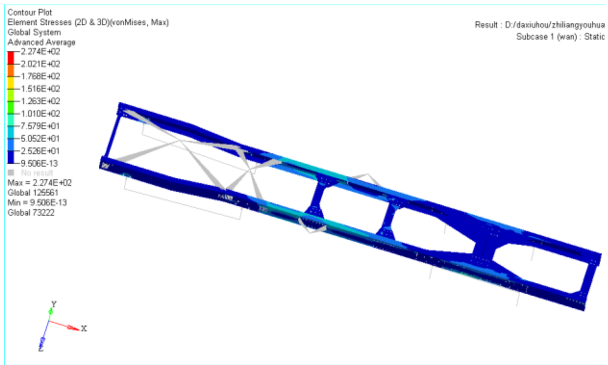


Figure 4. The first order torsion stress diagram of frame after optimization

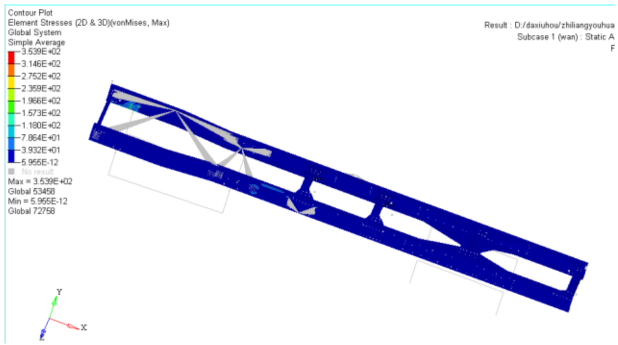


Figure 5. The first order bending stress diagram of the frame after optimization

2) *Weight Reduction Results and Discussions*

After seven iterative cycles of optimization calculation, the optimal results are determined. Table III presents the comparison between the optimized results and original values for each component. It can be seen that the thickness values for component No.1 and No.2 are reduced by 1mm comparing with their original values. On the other hand, the other components have slight increases in thickness. These changes indicated that the reduction of thickness in large components of No. 1 and No.2 would result in a significant decrease in overall weight. In the meantime, their influences on system performance could be compensated by increasing the thickness of the small components. This seems to be well agreed with common practices in many structure designs in which a combination of many small substructures is often employed to avoid overweight of a large structure.

TABLE III. THE COMPONENT THICKNESS OF THE OPTIMIZATION AND ADJUSTMENT RESULTS

Comp.(x_j)	Original thickness (mm)	Optimised thickness (mm)	Tuned thickness (mm)
1	8	7	7
2	8	7	7
3	8	9	9
5	7	7.68	8
6	7	7.87	8
7	7	7.77	8
9	8	8.01	8
10	8	8.74	9
11	7	7.78	8
12	7	8	8

TABLE IV. THE OPTIMIZATION BEFORE AND AFTER OF PERFORMANCE PARAMETERS COMPARISON

Parameters	Original	Optimised	Change.
Mass (Kg)	1076	990	86
Freq. 1 (Hz)	8.20	8.23	0.02
Freq. 2 (Hz)	10.73	10.80	0.07
σ_s (MPa)	219.7	227.4	7.7
σ_r （MPa）	342.3	353.9	11.6

After the optimization, the weight of the whole frame is reduced by 86 kg, achieving a weight reduction ratio of 8%. At the same time, as detailed in Table IV, the dynamic characteristics have little changes, i.e. the optimized new frame maintains the inherent characteristics of the original frame.

In addition, based on these new parameters from this lightweight design, a stress analysis is also performed using FE software. As show in Fig 4 and Fig 5, the stress distribution at the first order twist mode and bending mode meets the design requirement.

IV. CONCLUSION

This paper presents a new scheme for implementing lightweight design of a dump truck frame based on dynamic response analysis. It uses a test validated FE dynamic model to identify the most sensitive components that influence overall weight of the frame and the first two vibration modes which obtained through a gradient based sensitivity analysis. Using this approach the structural weight of the dump truck frame has been minimized and achieved a weight reduction of 8%, showing a significant improvement in structure design and demonstrating the effectiveness of the approach proposed.

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